CHAPTER 8

Influence of Soil Tillage on Slugs and Their Natural Enemies

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CONTENTS

8.1 INTRODUCTION

Terrestrial slugs and snails are gastropod molluscs belonging to the order Stylommatophora. Slugs have evolved from snails by losing or greatly reducing the external, hard, calcified shell, enabling them to live in small spaces[8] such as in the soil. Slugs are better able than snails to survive in cultivated fields. Moreover, because slugs do not need large supplies of calcium to build a protective shell, they can thrive in a wider range of soil types than snails, and they have become worldwide pests to many agricultural and horticultural crops. The main constraint on their distribution[86] is the need for a moist environment, an inevitable consequence of the loss of the protective outer shell.

Because slugs and their principal natural enemies are soil-dwelling animals, cultivation can cause major changes to their numbers and behavior. This chapter provides an overview of the influence of tillage systems on slug numbers and damage in field crops. This is followed by a more detailed examination of evidence about the influence of tillage practices on the abundance of slugs and their natural enemies and on interactions between slugs and crops. Finally, the role and effects of cultivation on integrated control of slug damage are considered. Snail pest problems are mentioned briefly, where appropriate.

In conventional moldboard plowing, the soil profile is inverted, usually to a depth of 20 cm, burying the residues of the previous crop. Usually, an important aim of both reduced-tillage systems (also known as noninversion tillage) and no-tillage systems is to leave at least a proportion of the residues of the previous crop on the soil surface to protect the soil from wind and water erosion.[30] This contrasts with the practice of disposing of cereal straw and stubble by burning *in situ*, which was common, for example, in the 1970s and 1980s in the United Kingdom.[79] Although straw burning does not kill significant numbers of slugs directly,[25,35] it decreases the availability of organic matter. Crop residues provide food for soil fauna in general[26] and slug populations and damage increase where straw or stubble are left *in situ*.[19,34,35]

8.2 SLUG PROBLEMS IN FIELD CROPS EMPLOYING REDUCED TILLAGE SYSTEMS

8.2.1 Winter Wheat and Other Small-Grain Cereals

Slugs, especially *Deroceras reticulatum* (Agriolimacidae) and *Arion* spp. (Arionidae), are important pests of small-grain cereals (wheat, barley, oats, rye, and triticale) in Western Europe,[31] killing seeds and seedlings as well as defoliating

seedlings. Slug problems in Great Britain are often severe even after plowing.[36,37,40,41,44] However, Edwards[25] reported briefly that direct-drilling cereals in rotation with oilseed rape favored the build up of slug populations. Subsequent studies have confirmed that direct drilling results in substantial increases in slug populations and damage in winter cereals in comparison to plowing,[19,34,61,92] but effects are not consistent between years and sites.[35] Reduced, noninversion methods of tillage generally have less effect on slug populations than plowing combined with subsequent cultivations to produce a seedbed for cereals.[35,41,42,61,92] Tillage with tines and disks was found by Kendall et al.[61] to cause greater suppression of slug populations than a single-pass noninversion-tillage system (Dutzi cultivator).

Similar results have been reported for cereals elsewhere in Europe. Slug damage was reported as one of the main problems of direct-drilled cereals in France.[21] Similarly, Garbe[29] reported that the incidence of slugs increased in cereal crops grown under reduced tillage compared to conventional plowing systems in Germany. Anken et al.[4] found that when six methods of cultivation were evaluated over 3 years in Germany for the establishment of winter wheat crops, direct drilling and reduced tillage were found to be suitable, but more effort was needed to control slugs under these systems than with plowing. Andersen[1] reported on the incidence of pests in five trials in Norway, where spring cereals were sown in plots plowed in autumn compared with plots harrowed in spring or plots with no-tillage over a 4-year period. Slugs (*D. reticulatum*), monitored by trapping in August, were significantly more abundant in plots with no-tillage than autumn plowing at two sites. However, at one site *D. reticulatum* were less abundant in plots with reduced tillage in spring compared to plots with autumn plowing.

Spaull[89] found that the incidence of grain hollowing by slugs in Scotland was greater where wheat had been sown in plots plowed in early September, soon after harvest of rape, than in plots plowed in late September. Treatment of the rape stubble with herbicide had no significant effect on slug damage.

8.2.2 Maize

Musick and Beasley[75] found that maize (corn) in Georgia, USA was susceptible to slugs where residues of the previous crop were left on the soil surface. Maize yields in a study in New York State, USA were lower with no-tillage than with conventional tillage, partly because of increased damage from slugs in the early stages of establishment.[66] In a project to encourage farmers to adopt no-till practices in maize production in New York State, slugs, together with armyworms (Lepidoptera), were the most frequently cited management problem.[100]

In a comparison of conventional-tillage, reduced-tillage, and no-tillage systems for maize over 4 years in Ohio, USA, Hammond and Stinner[49] reported that slug populations were greatest in no-tillage systems where crop residue cover was greatest and lowest when no residue was present. In a study of the effects of no-till and strip intercropping on maize in Ohio, slugs were more abundant and caused severe damage in no-till plots, in contrast to conventional tillage.[97] Willson and Eisley[102] analyzed records of key pests (slugs and four insect species) in maize crops in Ohio over a

10-year period in relation to tillage practices and crop rotation. The incidence of slugs exceeding the action threshold for control measures increased as tillage was reduced and was at its greatest in no-till maize. Hammond et al.[50] reported that many maize growers in Ohio were reluctant to use conservation-tillage practices for maize because of problems with slug damage. Hammond[47] and Hammond et al.[51] noted that slug problems in maize have increased in the Corn Belt in the Midwest in the U.S. as conservation-tillage methods have been adopted more widely. The main pest species are, in decreasing order of importance, *D. reticulatum, Deroceras laeve* (Agriolimacidae), *Arion subfuscus,* and *Arion fasciatus* (Arionidae). Slugs cause severe defoliation and stunting of maize, with maize at the five-leaf stage being seriously damaged. Juveniles of *D. reticulatum* are thought to cause the most damage by feeding on the crop in late May and June.

Slugs are also pests of direct-drilled maize in New Zealand. When wet weather followed direct drilling of maize into pasture sod, up to 44% of the seedlings were lost before emergence because of slug damage.[55] Crovetto[20] reported problems caused by slugs in direct-drilled maize at establishment in Chile.

8.2.3 Broad-Leaved Grain Crops

8.2.3.1 Oilseed Rape (Canola)

Slugs (mainly *D. reticulatum* and *Arion* spp.) do not attack rape seeds, but young seedlings may be killed or weakened by grazing in western Europe.[74] In a long-term tillage experiment started in 1969 and continued over more than 20 years in Switzerland with winter wheat, rape, and maize grown in rotation, damage by field slugs to oilseed rape was greater where noninversion tillage was used than where soil was plowed conventionally.[69] When winter rape was sown directly in late June into a winter wheat crop before harvest in Germany, the presence of high slug populations made it necessary to apply slug pellets at the time of sowing.[94]

Glen et al.[42] reported severe loss of stand (ca. 90%) of oilseed rape direct-drilled into the stubble of a cereal crop in England. There was moderate plant loss (ca. 40%) in plots cultivated by noninversion tillage and only slight damage on plowed plots. The severity of damage on the different cultivation treatments was positively correlated with the biomass of slugs in the upper 10 cm of soil at the time of establishment. The main species present at this site were *D. reticulatum* and *A. intermedius*.[92]

In a 3-year study in Germany, where the main pest slug species were *Deroceras agreste, D. reticulatum, Arion distinctus,* and *A. fasciatus*, slug numbers and activity in winter oilseed rape were increased by reduced tillage and especially by no-tillage in comparison to conventional plowing.[98] The extent of the increase in slug numbers and activity differed between years. In another comparison of conventional plowing, noninversion tillage, and no-tillage over a 3-year period in Germany, damage to oilseed rape by slugs was greatest where there was no-tillage, especially if the soil surface was wet at around date of sowing.[84,85]

8.2.3.2 Soya Bean

Hammond[47,48] reported that, as with maize, slug problems in soya bean have increased in the midwest corn belt of the U.S., as conservation-tillage methods have become more widely adopted. In contrast to maize, the most serious damage to soya bean is loss of stand rather than defoliation. Loss of soya bean stand results when seedlings are killed before they emerge from the seed furrow or from beneath the crop residue, or seedlings emerge and are then killed shortly afterwards. Severe defoliation also occurs to soya bean. Observations show that juveniles of *D. reticulatum* cause the most serious damage. However, *A. subfuscus* is also thought to be responsible for stand loss.

8.2.3.3 Sugar Beet

Ester and Geelen[27] reported that normally there are no problems with slugs in sugar beet in The Netherlands. However, sugar beet crops are susceptible to slug damage at establishment when they are direct-drilled into a mulch of dead organic matter from a previous cover crop.

8.2.3.4 Vegetable Brassicas

In experiments in northeastern U.S., cover crops of rye, hairy vetch (*Vicia villosa*), or both were sown in autumn and in the following spring were incorporated by tillage or left as dead mulch on the soil surface before planting brassicas.[70] The dead mulch led to increased slug incidence at one site.

8.2.3.5 Beans

The introduced slug *Sarasinula plebeia* (Veronicellidae) is an important pest of dried beans (*Phaseolus vulgaris*) and vector of human disease in Central America.[2] Severe damage to beans by *S. plebeia* is thought to be the result of no-till and poor control of broad-leaved weeds.[77] Field beans are generally grown in rotation with maize, with beans being planted among the erect maize stalks. Beans in this system are more severely attacked by slugs than beans grown in monoculture after intense soil preparation.[2] The use of herbicides to control broad-leaved weeds in maize is recommended as a means of reducing slug numbers in this no-till cropping system.[77]

8.2.4 Grass and Forage Legumes

There have been widespread reports from North America of severe slug damage to forage legume seedlings where the seeds have been drilled with little or no tillage into the sod of an established pasture that has been killed by herbicides. Welty et al.[99] reported that inadequate establishment of forage legumes with minimum tillage drills in Montana was associated with slugs killing seedlings. Similarly, Grant et al.[45]

reported that lucerne (alfalfa) seedling growth was significantly less, and seedling losses were significantly greater, in no-till than tilled plots in bluegrass sod in Kentucky. Slugs (mainly *D. reticulatum*) were, together with crickets (*Nemobius* spp.), the main pests responsible. Slug abundance (*D. laeve, A. fasciatus* and *D. reticulatum*) was negatively associated with the density of lucerne that established after sowing into 2-year-old lucerne fields by conservation-tillage methods in Pennsylvania.[13] Byers et al.[14] reported that methiocarb bait pellets, applied when red clover (*Trifolium pratense*), lucerne (*Medicago sativa*), and *Lotus corniculatus* were sown using a minimum-tillage drill into grass fields, sometimes controlled *D. reticulatum*, *D. leave,* and *A. fasciatus* and improved establishment of red clover and lucerne but not *L. corniculatus*. Byers and Templeton[15] studied factors limiting establishment of lucerne in grass (*Dactylis glomerata*) sod and concluded that if slugs (*D. reticulatum*) and the insect pest *Empoasca fabae* (Homoptera: Cicadellidae) were not controlled at the time of late spring plantings, then forage yield could be reduced substantially in the establishment year. Bahler et al.[5] found that in a 3-year study of lucerne establishment in oat stubble after minimum tillage in Ohio, slugs affected the crop when populations were high in one year out of three. In contrast to the above findings, Cardina and Hartwig[17] reported that slug-control measures did not lead to higher lucerne yields where seeds were sown into couch grass (*Elymus repens*) sod killed by glyphosate in Pennsylvania. They therefore concluded that slugs were not responsible for the poor growth of lucerne in this situation. Byers et al.[16] also reported no reduction in the establishment or yield of lucerne after maize in conservation-tillage systems. They attributed this to low slug numbers early in the growing season, lower than those usually recorded when lucerne is established in grass swards or residues of small grain crops.

In a comparative study of conventional and no-till establishment of white clover (*Trifolium repens*) in North Carolina,[83] clover failed to establish from no-till sowings because of slug damage but was largely unaffected in conventionally prepared seedbeds. Establishment of white clover and lucerne sown directly into grass (*Festuca arundinacea*) pastures in Georgia[12] was not enhanced by measures to control slugs and insect pests. There was a consistent decline in seedling numbers regardless of pesticide treatments, suggesting that other factors were responsible for this decline.

In New Zealand, the climate is only marginally suitable for slugs in many areas, but slugs can severely deplete seedling numbers during pasture establishment by no-till methods, in regions where there is adequate summer rainfall for slug survival.[7] Barker et al.[9] investigated interactions between seeding rate and pesticide treatments for perennial ryegrass (*Lolium perenne*), direct-drilled for pasture renovation, at three sites in northern New Zealand. At one site, *D. reticulatum* and *Deroceras panormitanum* (*D. caruanae*) aggregated to seed rows in increased numbers in response to increased sowing rates. Molluscicide applications significantly increased the numbers of surviving seedlings, in contrast to insecticide treatments (carbofuran and furothiocarb), which were ineffective. However, no effect of molluscicide treatments was recorded at the other two sites, whereas insecticide treatments had at least some effects.

8.2.5 General and Miscellaneous

Deep plowing is reported to reduce numbers of the snail pest *Bradybaena ravida* in Shaanxi Province, China[23] where they are important pests of wheat, maize, cotton, and other crops. The use of reduced methods of tillage by farmers is thought to have contributed to a recent increase in the severity of problems caused by four species of introduced snail pests in grain crops in southern Australia.[6]

In a 9-year study of the effects of five different cultivation systems in a rotation of winter wheat with maize and rape in Switzerland, greatest slug numbers were found following direct drilling.[3] Crovetto[20] found in his experience as a pioneer of no-till cropping that legumes direct-drilled into the residues of the previous crop in Chile were more sensitive to attack by slugs than cereal crops. Crops damaged at establishment were lentils, garbanzos, vetches, soybeans, lupins, lucerne, and maize. In contrast, slugs were not a problem in tilled soils.

8.3 EFFECTS OF TILLAGE ON SLUG ABUNDANCE

Slugs live in the soil as well as on the soil surface, and, although it is relatively simple to obtain estimates of the numbers of slugs active on the soil surface using some form of refuge traps,[54,104,105] numbers recorded depend on both activity and density. Thus, cultivation could influence numbers trapped through effects on either. More investment in time and effort is required to obtain absolute estimates of slug populations. Soil washing provides accurate estimates of numbers of eggs and active stages, but specimens are often recovered in poor condition, making identification difficult.[58] The soil-flooding process (cold-water process) devised by South[87] for grassland and modified by Hunter[58] for arable crops, provides specimens of active stages in excellent condition but does not provide any estimate of the number of eggs. Although slugs can live at considerable depths in the soil, Hunter[56] found that most are found in the upper 7.5 cm of soil in moist, mild conditions. For this reason, subsequent studies of the influence of cultivation on slug populations in arable fields in England have concentrated on slug numbers in the upper 10 cm of soil.[33,34–39,41,42,61,91]

Hunter[57] was the first to study the influence of cultivation on slug populations (mainly *D. reticulatum*, *Arion hortensis* agg. [Arionidae] and *Tandonia budapestensis* [Milacidae]). He did this in the loam soil of a market garden in northern England. When the whole garden was plowed in January 1964, he observed a significant 51% decline in the numbers of all three species and concluded that some of the slugs were probably killed by the cultivation. Part of the garden was then subjected to a series of 11 cultivation operations (including plowing twice) in May to June 1964 before grass was sown. Sampling of this cultivated area in September 1964 showed that there was a 91% reduction in slug numbers compared to the adjacent uncultivated area. Further observations in March 1965 of numbers before and immediately after plowing, cultivating twice, and rotavating once, showed a 56% reduction in slug numbers, which Hunter[57] concluded was due entirely to the mechanical effect

of the cultivations. The strength of the conclusions from this first study of the effects of cultivations on slug abundance is constrained by the lack of any uncultivated (control) treatment in January 1964 and March 1965, together with the lack of replication of the cultivated and uncultivated plots in May–June 1964. However, subsequent studies have, on the whole, confirmed the effects of cultivation as proposed by Hunter.[57]

In a replicated long-term experiment in England, Glen et al.[34] found that, in one year (1983), reduced tillage with tines to incorporate straw and stubble to 5 or 10 cm depth did not result in a significant reduction in slug numbers compared to no-till plots. However, in the following year, conventional plowing of straw and stubble to depths of 15 or 25 cm significantly reduced estimated numbers by 40 and 74%, respectively, and by 75 and 92% in 1985.[35] The strong effect of plowing at this site in 1984 and 1985, however, contrasted with a lack of any significant effect in these years in a second replicated experiment. At this second site, numbers were reduced by 99% only in the third year as a result of conventional plowing compared to the equivalent no-till plots (Glen et al.).[35]

In another replicated field experiment, Glen et al.[37] assessed densities and biomass of slugs (*D. reticulatum, D. panormitanum* and *Arion* spp., in decreasing order of abundance) in the upper 10 cm of soil in autumn 1988. On October 4, it was possible to compare slug populations on uncultivated plots with populations on plots that had been cultivated. One set of cultivated plots had been plowed only (to 225 mm depth, on September 28), and the other set had been plowed (to 225 mm, on September 5) followed by two secondary cultivation operations (on September 30 and October 1) before drilling winter wheat on October 3. Comparison of back-transformed means on these plots shows that plowing alone reduced slug numbers and biomass in the upper 10 cm of soil by 84 and 81%, respectively. Plowing plus secondary cultivations reduced numbers and biomass by 91 and 94%, respectively. The difference between plowing alone and plowing plus secondary cultivations was significant for slug biomass. The reduction due to plowing alone is greater than that reported by Hunter.[57] This could have resulted from slugs being located below the level of sampling on plots that were plowed only 6 d earlier. However, the effects of plowing plus secondary cultivations were similar to those reported by Hunter.[57]

Kendall et al.[61] summarized the mean slug numbers present each year in the top 10 cm of soil in plots with different tillage treatments over the first 3 years of two long-term replicated field experiments (labeled Fields 51 and 55) in England. Slug numbers (mainly *D. reticulatum* and *A. intermedius*) were consistently significantly higher on plots with no-tillage and noninversion tillage than on conventionally plowed plots in both experiments. In the second year on Field 55, numbers were significantly higher on no-till plots than on plots with noninversion tillage. In the third year on Field 51, the reverse was true, with one method of noninversion tillage (Dutzi cultivator) showing significantly higher numbers of slugs than no-till. In this latter experiment, two methods of noninversion tillage were compared. There were significantly more slugs after single-pass Dutzi cultivation than after tine and disk cultivation. Kendall et al.[61] attributed this difference to greater soil disturbance and more passes with the cultivator in the latter system. Symondson et al.[92] recorded slug populations on three different tillage treatments (no-tillage, noninversion tillage,

and plowing) at monthly intervals in the fourth year (1992) of one of the above experiments from July to September. In July, after harvest of a crop of oilseed rape but before cultivation, slug biomass was not affected by the previous autumn's cultivation treatments. However, in August and September, following noninversion tillage to incorporate stubble of the rape crop on all tillage plots, the biomass and mean individual weight of *D. reticulatum* were greater on the no-till plots (where rape residues were baled and removed, leaving stubble alone) than on tillage plots with the same treatment of rape residues. The biomass of *A. intermedius* showed a slightly different pattern, with biomass consistently significantly lower on plots that had been plowed in the previous autumn than on plots with noninversion tillage or no-till. This indicates that plowing had a longer-lasting effect on *A. intermedius* than *D. reticulatum*, perhaps because *A. intermedius* breeds in autumn when plowing is done or because plowing buries the food resources provided by straw and stubble out of reach of this species.

In two long-term studies of slug populations in southern England, substantial rapid declines in slug populations were observed in nonplowed plots following 3–4 years with high slug populations. One experiment was in continuous winter wheat,[35,19] and the other was in cereals grown in rotation with rape.[42,93] Following these declines, slug numbers remained at low levels for 2[42] to 4 years.[93] While numbers on nonplowed plots were still significantly higher than on plowed plots after the decline, the slugs on the nonplowed plots became insignificant as pests. Weather was favorable at the times of both population declines and afterwards. Moreover, agronomic conditions remained similar before and afterwards. This pattern suggests that natural enemies could be responsible for such declines to relatively stable low levels.

8.4 EFFECTS OF TILLAGE ON ABUNDANCE OF NATURAL ENEMIES

Pest slugs are attacked by a wide range of natural enemies including vertebrates (birds, mammals, reptiles, and amphibians),[43,88] parasitic flies,[63,82] and arachnids.[76] However, the main groups of natural enemies studied in relation to predation on slugs are Coleoptera,[91] in particular carabid beetles, which are frequently found at high density on cultivated land. While many carabids have been shown to eat slugs,[65,91] the carabid beetle *Pterostichus melanarius* has, more importantly, been shown to be capable of affecting both the temporal and spatial dynamics of slugs in the field.[10,11,93] This carabid is frequently the dominant species in arable crops in much of Europe and North America[67,95] and has been shown to respond to differences in the timing and type of cultivation technique applied.[92]

Though found at high density in both arable and grassland habitats,[24,67,68,81,93] *P. melanarius* appears to be well-adapted to the periodic disturbance caused by cultivation and other agricultural practices, with no dependence on field margins as overwintering sites.[53] However, the timing of cultivation can have a critical effect on predator numbers. This carabid breeds in the late summer and autumn, mainly overwintering as larvae and pupating in the spring.[24,28] Significant numbers of the new generation of *P. melanarius* adults then appear in the field in midsummer. Spring cultivation was

shown by Fadl et al.[28] and Purvis and Fadl[80] to have a highly detrimental effect on numbers of newly emerging *P. melanarius* adults, reducing their density by as much as 80%. Autumn cultivation, however, had no significant effect on *P. melanarius* number. The reason for the difference appears to be that pupating larvae, and the pupae themselves, are highly susceptible to disturbance in the spring when cultivation may either physically destroy them or exposes them to predation. The negative effects of spring cultivation were sometimes offset by immigration of carabids from surrounding areas, a phenomenon that is possible only within a heterogeneous, patchy landscape.[28] A later study showed that *P. melanarius* was most strongly associated with autumn cultivated fields and uncultivated young leys.[81]

In general, carabids are negatively affected by deep plowing and enhanced by direct drilling.[64] Kendall et al.[60] (see Chapter 11 in this book) showed that the type of autumn cultivation employed had an effect on numbers of larger carabids (a positive correlation has been found between carabid size and predation on slugs).[96] Following cultivation there were significantly greater numbers of larger carabids (mainly *P. melanarius*) caught in pitfall traps in direct-drilled plots than in plowed plots, with intermediate numbers in plots cultivated by noninversion tillage. These differences did not persist through the winter. Pitfall traps give a combined measure of activity and density. However, as surface litter found on direct-drilled land inhibits beetle activity, while beetles can move more freely on cultivated land where crop residues have been removed or incorporated, it is probable that the differences measured underestimated population differences between the direct-drilled and cultivation treatments. A later study[61] that used principal-component analysis on data sets from two experiments over 3 years showed that adult *P. melanarius* were associated with nonplowed arable land.

Symondson et al.[92] also examined the effects of different forms of autumn cultivation and methods of crop residue disposal on both *P. melanarius* and their slug prey following a crop of oilseed rape. The main effect was a significantly greater number of *P. melanarius* in the direct-drilled plots, where the crop residue was removed, compared with the tilled treatments, where the residue was incorporated. As beetles in direct-drilled plots were better fed, with a greater biomass of food in their foreguts than in plots that were tilled, it may well have been the case that the beetles were simply aggregating to where there was more food, rather than directly responding to the physical effects of cultivation. In the month following harvesting and crop residue disposal there were significantly more slugs in the direct-drilled plots, and beetles in those plots contained greater quantities—and concentrations—of slug proteins in their foreguts than beetles in the tilled plots.

8.5 EFFECTS OF TILLAGE ON INTERACTIONS BETWEEN SLUGS AND CROPS

8.5.1 Slug Behavior in Relation to Tillage

Slug behavior, and thus damage to cereals, is profoundly influenced by cultivation and drilling practices. Characteristically, slug damage to winter wheat is less severe on headlands (the strips bordering the edge of fields) than in the middle of cultivated fields because machinery turning at the edge of the field consolidates the soil.[44]

Winter wheat is especially vulnerable to slug damage at establishment if seedbed conditions enable the slugs to move through the soil and feed on the embryo of the seeds or on the shoots and roots at the point where they emerge from the seeds.[31] Direct-drilled crops are vulnerable to this type of damage where the drill slit does not close over properly after seeds are sown. Under these conditions, slugs simply move along the narrow space of the open seed drill, killing seeds or seedlings one after the other. The ability of slugs to feed readily on direct-drilled crops probably explains why Glen et al.[34,35] generally found that damage to winter wheat was less severe after cultivation than on no-till plots, even though slug numbers were not necessarily reduced by cultivation treatments.

Winter wheat sown into cultivated seedbeds is also vulnerable to slugs where cultivations have produced a seedbed with a high proportion of large clods (soil aggregates). Laboratory studies have demonstrated that three pest species of slugs, *D. reticulatum,*[22,71,72,90] *A. hortensis* agg., and *T. budapestensis,*[22] are all able to find and kill wheat seeds much more readily in coarse, cloddy soil than in fine soil, but the vulnerability of seeds can be reduced by seedbed consolidation. However, Stephenson[90] noted that consolidation of dry clods had no significant influence on the percentage of seeds killed, because this consolidation failed to break down soil aggregates. Similarly Glen et al.[36] found that rolling a dry cloddy seedbed after drilling failed to break down clods and had no significant effect on seed kill by slugs in the field.

Despite the tendency for larger numbers of slugs to survive reduced tillage compared with plowing, the more rapid cultivation achieved by reduced tillage methods may help contribute to reduced slug damage to winter wheat seeds. This would result if the farmer is able to cultivate land in a brief window of favorable soil and weather conditions where it is possible to prepare the fine, firm seedbeds that deter slug attack on wheat seeds. Moreover, improvements in soil structure resulting from shallow incorporation of crop residues should, over time, make it more likely that the farmer could prepare such seedbeds.

8.5.2 Vulnerability of Crop to Damage, in Relation to Tillage

Winter wheat seeds are highly vulnerable if slugs are able to find seeds that are poorly covered by soil.[71,72] Such seed is not only found more readily but also germinates more slowly and thus remains at the most vulnerable stage for longer than well-covered seed.[71] The shoots are often damaged once they emerge, but, provided that young plants are growing well, they can withstand considerable above-ground grazing damage. The ability of cereals to withstand such grazing results, in part, from the growing points remaining below ground at the base of the shoot, where they are protected from damage if there is adequate soil cover. This protected meristematic tissue is in marked contrast to dicotyledonous crops such as oilseed rape,[74] where the growing point is carried above ground at germination. This difference in growth habit may explain the observation by Crovetto[20] that legumes direct-drilled into the residues of the previous crop in Chile were more sensitive to attack by slugs than cereal crops. Also, Glen et al.[42] suggested that a given population of slugs in soil caused much more severe damage to winter oilseed rape than to winter wheat.

Seedlings of all crops are especially at risk from slug damage if tissue losses are not compensated for by growth.[73] Lack of moisture for seed germination and seedling growth due, for example, to poor soil cover can result in slow growth in cloddy seedbeds. Soil capping or overly compacted seedbeds can also result in slow growth due to a poor supply of oxygen to the plant roots. Waterlogging of soil and low soil temperatures are other common causes of slow growth.

8.6 INTEGRATED CONTROL OF SLUG DAMAGE IN RELATION TO TILLAGE

8.6.1 Damage Forecasting and Risk Assessment in Relation to Tillage

Experience in a wide range of crops clearly shows that, by the time damage becomes evident, either as gaps in the rows of an emerging crop or as grazing damage to seedlings, it may already be too late to take effective action. Reliable forecasts of potentially damaging slug populations would therefore be extremely valuable.[31,39,46,74,78] Accurate assessments of slug population density in soil are needed for damage forecasting. However, because direct methods of estimating slug density are slow and labor-intensive, consultants and growers currently rely on using refuge traps, where numbers recorded depend on both slug abundance and surface activity. Slug activity is dependent on temperature and surface moisture,[18,104–107] but it is almost certainly considerably disrupted by cultivation. This may explain why Glen et al.[40] found that slug activity on the soil surface at drilling, and between drilling and emergence, was poorly correlated with damage to wheat seeds, whereas the best predictor was the peak number of slugs trapped before the soil was disturbed by cultivation. A further disadvantage of refuge traps is that they selectively record the larger individuals in the population.[33] Thus, if the majority of the slug biomass in the soil consists of juveniles, records from these traps might fail to correlate with crop damage.

8.6.2 Tillage and Related Cultural Control Measures

Preparation of fine, firm seedbeds reduces the risk of seeds and seedlings being killed by slugs. This is especially important in protecting wheat seeds from slugs. However, there are limitations to this method of control. First, for winter wheat crops, farmers must be careful not to produce such a fine seedbed that the soil caps as a result of heavy rainfall during the winter months, causing slow growth due to restricted air supply to the roots. Second, it is often not possible to produce a fine seedbed on clay or silt soils because when the soil is too dry or wet it does not break down into fine aggregates but remains as coarse clods. In such situations, rolling is a recommended method of control because clods are usually broken down to give finer aggregates[89] or squashed, thereby reducing the size of air spaces.[22] However, if the clods are dry and hard, rolling may not contribute to slug control because the

clods are not broken down.[36,90] Moreover, rolling is not possible in wet soil conditions because of smearing and the risk of soil capping.

When farmers have to drill cereal seeds into a coarse, cloddy seedbed on heavy land, the severity of slug damage can be greatly reduced by increasing the drilling depth from the normal 30 mm to 40 or 50 mm.[37,41] This increased drilling depth is readily achieved and does not cause an unacceptable delay in emergence and may in some cases speed germination because there is often more moisture, as well as better soil cover of seeds, at this depth in cloddy seedbeds.[101] Glen et al.[37] showed that drilling at a depth of 40 mm rather than 20 mm was as effective as a broadcast application of molluscicide bait pellets in reducing the kill of wheat seeds and seedlings, and in one experiment, drilling at 50 mm rather than 25 mm was also associated with an increase in yield.[41]

8.6.3 Sowing Date

Winter wheat seeds sown later in autumn in the U.K. tend to be at greater risk of slug damage than wheat sown earlier.[40] However, there is considerable variability in this relationship between sowing date and damage, and it may relate to the greater likelihood that wheat will be sown into coarse seedbeds in late autumn.

Byers et al.[14] noted the importance of sowing time for the severity of slug damage to direct-drilled legumes in Pennsylvania: late spring and summer sowings without pesticides sustained considerable seedling losses, whereas seedlings from early spring sowings in untreated areas were injured less. Similarly, Byers and Templeton[15] concluded that direct-drilling lucerne very early in spring avoided losses from *D. reticulatum* as well as the insect pest *Empoasca fabae* (Homoptera: Cicadellidae). Hammond[48] recommended early sowing of soya bean so that plants achieve maximum growth before slugs become active in late spring.

8.6.4 Biological Control

The role of carabid beetles, especially *P. melanarius*, as slug predators has already been discussed. The slug-parasitic nematode, *Phasmarhabditis hermaphrodita*, has been used successfully as an inundative biological control agent to protect a range of crops from slug damage.[32] In dry soil conditions, shallow cultivation by tines after nematode application was found to result in improved efficacy, probably as a result of protection of nematodes from desiccation.[103] Hass et al.[52] compared three types of soil cultivation for incorporating nematodes into soil. They found no reduction in nematode efficacy when nematodes were incorporated using tines, which mix the soil in a relatively gentle way, or using a Roterra, which has a vigorous horizontal circular action. However, a Dutzi cultivator, which mixes soil in a vertical plane, rendered nematodes ineffective, probably because it incorporated nematodes deeper into the soil than the other two methods. *P. hermaphrodita* is not currently used for slug control in field crops because of its high cost and limited

storage life, even under refrigerated conditions, in comparison with chemical molluscicides.[32]

8.6.5 Chemical Control

Molluscicidal bait pellets are important for controlling slug damage and are widely used in reduced tillage and no-till systems. For example, Byers and Templeton[15] reported that when lucerne was established in Pennsylvania using no-till methods in grass sod, *D. laeve* and *D. reticulatum* were controlled by methiocarb bait pellets, and this was thought to contribute to greater dry matter yield of lucerne on treated plots during the establishment year. Crovetto[20] reported that in no-till systems in Chile, molluscicidal bait pellets were quickly consumed but were not entirely effective. Methiocarb pellets were found to control slugs only after two to three applications. He recommended application of controls with the first autumn rains and in the spring before planting. Hammond et al.[50] found that molluscicides applied in early May in the U.S. Corn Belt did not prevent juvenile slugs (mainly *D. reticulatum*) from becoming abundant in mid-June. These slugs then caused severe defoliation of maize seedlings, similar to that on untreated plots. However, the number of juvenile slugs was reduced and defoliation was prevented by molluscicide treatments applied in late May or early June. These authors suggested that the reason for the success of the later treatments was probably because the molluscicides were applied close to the time of egg hatch. In a 3-year study in Germany, four of six molluscicide treatments applied to protect oilseed rape grown with reduced or zero tillage were followed by a 2- to 3-week reduction in slug activity on the soil surface in treated plots.[98]

Where the soil is cultivated, the use of molluscicidal bait pellets must be carefully integrated with tillage. Best control is normally achieved by broadcasting pellets on the soil surface shortly before or after the crop is drilled. If this is done before drilling, it is important that the soil not be cultivated for at least 3 d afterwards.[46] However, because of the importance of timely sowing in maximizing crop establishment, growers are not advised to delay sowing simply to apply bait pellets before drilling. In most situations, the best practical option is to broadcast bait pellets on the soil surface immediately after drilling.[46]

Bait pellets can also be applied as an admixture with seeds at drilling. This appears to be an attractive option for winter wheat seeds because bait pellets are then close to the seeds, which are highly vulnerable to slugs. This method of application is attractive also because methiocarb bait pellets drilled with seeds are less likely to kill nontarget species such as adult carabid beetles[62] and mice[59] than pellets broadcast on the soil surface. However, bait pellets drilled with wheat seeds may be unavailable to slugs,[39] especially if the recommended cultural measures are adopted to protect seeds from slugs. Shallow-sown seeds in a coarse seedbed, which are vulnerable to slug damage, can be protected by bait pellets drilled with them, but this protection is likely to be no better than would be achieved by drilling seed slightly deeper in a coarse seedbed.[39] To improve the protection from seed kill obtained by deeper drilling alone bait pellets should be broadcast on the soil surface after drilling slightly deeper than normal.[37,39]

8.7 CONCLUSIONS

8.7.1 Effects of Tillage on Slug Abundance

Based on his study of the impact of cultivations on slugs numbers, Hunter[57] concluded that there was a considerable danger that slug populations and damage would increase because the introduction of new herbicides would make cultivations less necessary. This conclusion is supported by experience since then in a wide range of crops grown worldwide with reduced tillage and, especially, zero tillage, where slugs have regularly caused severe damage over large geographical areas where they were previously unknown as pests. The broad conclusion that emerges from the studies reviewed here is that the greater the number of cultivation operations and the more intensive the method of cultivation, the more likely it is that slug numbers will be substantially reduced. Noninversion methods of tillage generally are less effective in reducing slug populations than plowing and subsequent cultivations to produce a seedbed for sowing field crops. However, in regions such as western Europe where environmental conditions are highly suited to slugs, sufficient slugs may still survive to cause severe damage to seeds and seedlings of a wide range of crops.

8.7.2 Effects of Tillage on Slug Behavior

In addition to the effects of tillage on slug populations, availability and accessibility of cereal seeds and seedlings to slugs are considerably influenced by tillage practices. Cereal crops sown in a rough seedbed in soil with a high clay or silt content are especially susceptible to slug damage because slugs are able to move through the air spaces between soil aggregates and gain access to the seeds. Although reduced tillage results in increases in slug populations, these practices result in improvements in soil structure and timeliness of cultivation, which can make it possible to prepare finer seedbeds that deter slug attack on cereal seeds because seeds are closely covered by fine soil aggregates and are therefore hidden from slugs. Tillage practices resulting in slow seedling growth increase the vulnerability of seedlings to slug damage.

8.7.3 Effects of Tillage on Natural Enemies of Slugs

In long-term studies of slug populations, substantial declines in slug populations on nonplowed plots have been observed following 3 years or more with high slug populations, in circumstances suggesting that natural enemies were involved. The identity of these natural enemies remains unknown, but possibilities include predators, pathogens, and parasites. Among predators, polyphagous carabid beetles, especially *P. melanarius*, may have a substantial impact on slug populations in cropland. Greater numbers of *P. melanarius* are found in fields cultivated in the autumn than in spring. Spring cultivation can cause severe reductions in numbers of these beetles, at least in the short term. Among the autumn cultivation treatments, the greatest numbers of beetles are associated with direct drilling, with fewest where the land

is plowed. The beetles have been shown to aggregate to patches in fields with higher slug density, where they were able to limit growth in slug numbers.[10,11] Between years the beetle predators were capable of affecting slug numbers.[93] As numbers of these beetles are highest in the summer and early autumn, leading up to the time when winter crops are sown and vulnerable to attack by slugs, use of cultivation treatments that foster higher populations of these slug predators can make a useful contribution to an integrated slug-control strategy. Fostering of large populations of these carabids (for example, by avoiding use of inappropriate insecticides when beetle numbers are high) may help to offset the negative effects of direct drilling and crop residue incorporation in the soil, which can lead to higher numbers of slugs.

The nematode *P. hermaphrodita*, a parasite capable of killing slugs, has been developed as a commercial biological control agent for use against slugs and gives good control of slug damage when applied to moist soil. In dry soil conditions, shallow soil tillage following nematode application to soil has been found to result in improved efficacy, probably as a result of improved protection of nematodes from desiccation. However, the high cost of this nematode precludes its use in arable crops.

8.7.4 Integrated Control of Slug Damage in Relation to Tillage

Chemical control using molluscicidal bait pellets must be carefully integrated with tillage practices for reliable control of slug damage. For example, cultivation should be avoided for at least 3 d after molluscicide application. Also, because tillage practices should make it difficult for slugs to find vulnerable seeds, bait pellets should not, in general, be drilled with the seeds where they could be unavailable to slugs but broadcast on the soil surface, where pellets are readily found by slugs.

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